



## MINIATURE BROADBAND TRANSDUCER

### DESCRIPTION

#### TECHNICAL FIELD

The present invention relates to miniature silicon transducers.

#### BACKGROUND OF THE INVENTION

The use of silicon based capacitive transducers as microphones is well known in the art. Typically, such microphones consist of four elements: a fixed backplate; a highly compliant, moveable diaphragm (which together form the two plates of a variable air-gap capacitor); a voltage bias source and a buffer.

The batch fabrication of acoustic transducers using similar processes as those known from the integrated circuit technology offers interesting features with regard to production cost, repeatability and size reduction. Furthermore, the technology offers the unique possibility of constructing a single transducer having a wide bandwidth of operation with a uniform high sensitivity. This provides for a transducer that, with little or no modification, can be used in such diverse applications as communications, audio, and ultrasonic ranging, imaging and motion detection systems.

The key to achieve wide bandwidth and high sensitivity lies in creating a structure having a small and extremely sensitive diaphragm. Designs have previously been suggested in U.S. Patent No. 5,146,435 to Bernstein, and in U.S. Patent No. 5,452,268 to Bernstein. In these structures the diaphragm is suspended on a number of very flexible movable springs. However, the implementation of the springs leads to an inherent problem of controlling the acoustic leakage in the structure, which in turn affects the low frequency roll-off of the transducer. Another approach is to suspend the diaphragm in a single point, which also provides an extremely sensitive structure. See U.S. Pat. No. 5,490,220 to Loeppert. Unfortunately, in this case the properties of the diaphragm material become critical, especially the intrinsic stress gradient which causes a free film to curl. Eventually, this leads to a similar problem for this structure concerning the reproducibility of the low frequency roll-off of the transducer.

The two mechanical elements, the backplate and diaphragm, are typically formed on a single silicon substrate using a combination of surface and bulk micromachining well known in the art.

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technique has its disadvantages. It results in making the thin film less etch resistant to HF acid, increasing the difficulty and expense of manufacture. An additional solution known in the prior art would be to increase the thickness of the sidewall supporting the raised backplate thereby increasing the sidewall's ability to resist the intrinsic tendency of the thin film to deflect. While this sounds acceptable from a geometry point of view, manufacture of a thick sidewall when the raised microstructure is made using thin film deposition is impractical.

The object of the present invention is to solve these and other problems.

#### SUMMARY OF THE INVENTION

One aspect of the present invention results from a realization that a diaphragm has the highest mechanical sensitivity if it is free to move in its own plane. Furthermore, if the diaphragm is resting on a support ring attached to the perforated member, a tight acoustical seal can be achieved leading to a well controlled low frequency roll-off of the transducer. Additionally, if a suspension method is chosen such that the suspension only allows the diaphragm to move in its own plane and does not take part in the deflection of the diaphragm to an incident sound pressure wave, complete decoupling from the perforated member can be achieved which reduces the sensitivity to external stresses on the transducer.

In one embodiment, the present invention features an acoustic transducer consisting of a perforated member and a movable diaphragm spaced from the perforated member. The spacing is maintained by a support ring attached to the perforated member upon which the diaphragm rests. There are means for suspending the diaphragm such that the diaphragm is free to move in its own plane, thereby maximizing the mechanical sensitivity of the diaphragm. The suspension is achieved by restraining the diaphragm laterally between the support ring and the substrate attached to the perforated member. There are means for applying an electrical field between the perforated member and the diaphragm. There are also means for detecting the change of electrical capacitance between the perforated member and the diaphragm as the diaphragm deflects due to an incident acoustic sound pressure wave.

The thickness and size of the diaphragm are chosen such that the resonance frequency of the diaphragm is larger than the maximum acoustical operating frequency. Similarly, the dimensions of the perforated member are chosen such that the resonance frequency is larger than the maximum acoustical operating frequency. The perimeter at which the perforated member is attached to the substrate can optionally be shaped to minimize the curvature of the perforated member due to

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assists in the construction and diaphragm release process, but once in operation the electrostatic attraction brings the diaphragm into contact with the perforated member support structure. Contrary to that taught by U.S. Patent No. 5,146,435 to Bernstein, and U.S. Patent No. 5,452,268 to Bernstein, the spring of the present invention plays an insignificant role in establishing the diaphragm compliance. There also are means for applying an electrical field between the perforated member and the diaphragm. There are further means for detecting the change of electrical capacitance between the perforated member and the diaphragm as the diaphragm deflects due to an incident acoustic sound pressure wave.

The thickness and size of the diaphragm is chosen such that the resonance frequency of the diaphragm is larger than the maximum acoustical operating frequency. Similarly, the dimensions of the perforated member are chosen such that the resonance frequency is larger than the maximum acoustical operating frequency. The perimeter at which the perforated member is attached to the substrate can optionally be shaped to minimize the curvature of the perforated member due to intrinsic stress in said perforated member. The high compliance suspension springs are made rigid enough for the structure to be made by micro machining technology, and yet compliant enough to mechanically decouple the diaphragm from the perforated member and to ensure that the in-plane resonance frequency of the diaphragm and springs is as small as possible compared to the intended low roll-off frequency of the transducer to prevent in-plane vibration of the diaphragm in operation. The support ring is formed in the perforated member and sets the size of the active part of the diaphragm. The height of the support ring defines the initial spacing between the diaphragm and the perforated member. There are one or more openings in the support ring, providing an acoustical path from the back chamber of the transducer to the surroundings thereby eliminating any barometric pressure from building up across the diaphragm. The low roll-off frequency of the transducer is limited by the corner frequency formed by the acoustical resistance of the openings and the acoustical compliance of the back chamber. The perforated member has a systematic pattern of openings providing a low acoustical resistance of the air flowing to and from the air gap between the movable diaphragm and the perforated member. The systematic pattern and size of the openings are chosen such that the high roll-off frequency of the transducer is limited by the corner frequency introduced by the acoustical resistance in combination with the acoustical compliance of the diaphragm and back chamber of the transducer. The perforated member, support ring, suspension

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FIG. 11 is a cross-sectional perspective view of the acoustic transducer of FIG. 4;

FIG. 12 is a cross sectional schematic of a raised microstructure known in the prior art;

FIG. 13 is a cross sectional perspective view of a raised microstructure embodying the present invention;

FIG. 14 is a cross section of the raised microstructure of FIG. 13; and

FIG. 15 is a plan view of FIG. 13, taken along line 11-11.

#### DETAILED DESCRIPTION OF THE INVENTION:

While this invention is susceptible of embodiment in many different forms, there is shown in the drawings and will herein be described in detail preferred embodiments of the invention with the understanding that the present disclosure is to be considered as an exemplification of the principles of the invention and is not intended to limit the broad aspect of the invention to the embodiments illustrated.

Referring now to the drawings, and particularly to FIGS. 1-3, an acoustic transducer in accordance with the present invention is disclosed. The acoustic transducer 10 includes a conductive diaphragm 12 and a perforated member 40 supported by a substrate 30 and separated by an air gap 20. A very narrow air gap or width 22 exists between the diaphragm 12 and substrate 30 allowing the diaphragm to move freely in its plane, thereby relieving any intrinsic stress in the diaphragm material and decoupling the diaphragm from the substrate. A number of small indentations 13 are made in the diaphragm to prevent stiction in the narrow gap between the diaphragm and substrate. The lateral motion of the diaphragm 12 is restricted by a support structure 41 in the perforated member 40, which also serves to maintain the proper initial spacing between diaphragm and perforated member. The support structure 41 may either be a continuous ring or a plurality of bumps. If the support structure 41 is a continuous ring, then diaphragm 12 resting on the support structure 41 forms tight acoustical seal, leading to a well controlled low frequency roll-off of the transducer. If the support structure 41 is a plurality of bumps, then the acoustical seal can be formed either by limiting the spacing between the bumps, by the narrow air gap 22, or a combination thereof.

The conducting diaphragm 12 is electrically insulated from the substrate 30 by a dielectric layer 31. A conducting electrode 42 is attached to the non-conductive perforated member 40. The perforated member contains a number of openings 21 through which a sacrificial layer (not shown) between the diaphragm and perforated member is etched during fabrication to form the air gap 20

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between the diaphragm 12 and the perforated member is etched during fabrication to form the air gap 20 and which later serves to reduce the acoustic damping of the air in the air gap to provide sufficient bandwidth of the transducer. A number of openings are made in the support structure 41 to form a leakage path 14 (FIG. 6) which together with the compliance of the back chamber (not shown) on which the transducer can be mounted forms a high-pass filter resulting in a roll-off frequency low enough not to impede the acoustic function of the transducer and high enough to remove the influence of barometric pressure variations. The openings 14 are preferably defined by photo lithographic methods and can therefore be tightly controlled, leading to a well defined low frequency behavior of the transducer. The attachment of the perforated member along the perimeter 43 can be varied to reduce the curvature of the perforated member due to intrinsic internal bending moments. The perimeter 43 can be smooth (FIGS. 5-7) or corrugated (FIGS. 8 and 11). A corrugated perimeter provides additional rigidity of the perforated member thereby reducing the curvature due to intrinsic bending moments in the perforated member.

In operation, an electrical potential is applied between the conductive diaphragm 12 and the electrode 42 on the perforated member. The electrical potential and associated charging of the conductors produces an electrostatic attraction force between the diaphragm and the perforated member. As a result, the free diaphragm 12 moves toward the perforated member 40 until it rests upon the support structure 41, which sets the initial operating point of the transducer with a well defined air gap 20 and acoustic leakage through path 14. When subjected to acoustical energy, a pressure difference appears across the diaphragm 12 causing it to deflect towards or away from the perforated member 40. The deflection of the diaphragm 12 causes a change of the electrical field, and consequently capacitance, between the diaphragm 12 and the perforated member 40. As a result the electrical capacitance of the transducer is modulated by the acoustical energy.

A method to detect the modulation of capacitance is shown in FIG. 9. In the detection circuit 100, the transducer 102 is connected to a DC voltage source 101 and a unity-gain amplifier 104 with very high input impedance. A bias resistor 103 ties the DC potential of the amplifier input to ground whereby the DC potential "V<sub>bias</sub>" is applied across the transducer. Assuming in this circuit a constant electrical charge on the transducer, a change of transducer capacitance results in a change of electrical potential across the transducer, which is measured by the unity-gain amplifier.

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grooves 122 of a squared cross section. The effect of corrugating the side wall in this manner is to create segments 124 of the sidewall 114 that are radial, as is the intrinsic tension  $T$  of the plate 112. By making portions of the sidewall 114 radial, as is the tension  $T$ , the sidewall 114 is stiffened. It has been found that the sidewall 114 of the prior art, which is tangential to plate 112, is easily bent as compared to the radial segments 124 of the present invention.

Other geometries than that shown in FIGS. 13-15 of the corrugations or ridges 120 and grooves 122 can be imagined and used effectively to increase the sidewall's 114 ability to resist moment  $M$  and the geometry depicted in the FIGS. 13-15 is not intended to limit the scope of the present invention.

For example, a generally annular geometry, generally triangular geometry or any combination or variation of these geometries or others could be utilized for the ridges 122 and grooves 124.

In the preferred embodiment, the corrugations are radial and hence the sidewalls 114 are parallel to the tension in the backplate 112. Furthermore, the sacrificial material is etched in such a way that the sidewalls 114 are sloped with respect to the substrate to allow good step coverage as the thin film backplate 112 is deposited.

While the specific embodiments have been illustrated and described, numerous modifications come to mind without significantly departing from the spirit of the invention and the scope of protection is only limited by the scope of the accompanying Claims.

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9. The acoustic transducer of claim 1 wherein said cover member includes a support structure having one or more openings made therein to provide a low frequency pressure equalization path across said diaphragm.
10. The acoustic transducer of claim 1 wherein said cover member includes a support structure and said diaphragm is held in position against said support structure by electrostatic attraction forces generated between said diaphragm and said perforated member due to said electrical field.
11. The acoustic transducer of claim 1 wherein said diaphragm and cover member are made on a silicon wafer using photo lithographic techniques.
12. The acoustic transducer of claim 1 wherein said diaphragm and cover member are made from one or more materials consisting of carbon-based polymers, silicon, polycrystalline silicon, amorphous silicon, silicon dioxide, silicon nitride, silicon carbide, germanium, gallium arsenide, carbon, titanium, gold, iron, copper, chromium, tungsten, aluminum, platinum, palladium, nickel, tantalum and their alloys.
13. An acoustic transducer comprising:  
a cover member having a planar surface with a plurality of perforations therein;  
a substrate operably attached to said perforated member;  
a diaphragm positioned between said cover member and said substrate, said diaphragm laterally movable within a plane parallel to said planar surface of said cover member;  
a circuit operably coupled to said diaphragm to apply an electrical field in the space between said perforated member and diaphragm;  
a circuit operably coupled to said diaphragm and responsive to changes in electrical capacitance between said cover member and said diaphragm; and  
wherein said cover member includes a support structure having one or more openings made therein to provide a low frequency pressure equalization path across said diaphragm.
14. The acoustic transducer of claim 13 wherein said perimeter is corrugated.
15. The acoustic transducer of claim 13 wherein said cover member and said substrate define a lateral restraint.
16. The acoustic transducer of claim 13 wherein one or more indentations are made in said diaphragm to prevent stiction between said diaphragm and said substrate.

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28. The raised microstructure of claim 25 wherein the rib has a generally triangular cross section.
29. The raised microstructure of claim 25 wherein the rib has a generally rectangular cross section.
30. The raised microstructure of claim 25 wherein the thin-film comprises one plate of a silicon based capacitive transducer.
31. The raised microstructure of claim 25 wherein the thin-film comprises a rigid backplate of a silicon based microphone.
32. A silicon based electret microphone having a backplate comprising:
  - a generally planar thin-film;
  - a sidewall supporting the film;
  - wherein the sidewall has at least one rib formed therein.
33. The microphone of claim 32 wherein the sidewall is corrugated.
34. The microphone of claim 32 wherein the rib has a generally arcuate cross section.
35. The microphone of claim 32 wherein the rib has a generally triangular cross section.
36. The microphone of claim 32 wherein the rib has a generally rectangular cross section.
37. The microphone of claim 32 wherein the sidewall includes a plurality of ribs.
38. The microphone of claim 37, wherein the ribs are equally spaced about the sidewall.
39. A raised microstructure for use in a silicon based device, the raised microstructure comprising:
  - a generally planar element with a first thickness and a periphery;
  - a sidewall with a second thickness;
  - said sidewall supporting said planar element at said periphery above a substrate at a distance;
  - wherein said sidewall has a plurality of ribs formed therein.
40. The raised microstructure of claim 39 wherein said first thickness is small compared to the lateral extent of the said planar element.
41. The raised microstructure of claim 39 wherein said second thickness is approximately equal to the said first thickness.
42. The raised microstructure of claim 39 wherein said distance is large compared to said second thickness.

57. The acoustic transducer of claim 45 wherein said diaphragm and cover member are made on a silicon wafer using photo lithographic techniques.

58. The acoustic transducer of claim 45 wherein said diaphragm and cover member are made from one or more materials consisting of carbon-based polymers, silicon, polycrystalline silicon, amorphous silicon, silicon dioxide, silicon nitride, silicon carbide, germanium, gallium arsenide, carbon, titanium, gold, iron, copper, chromium, tungsten, aluminum, platinum, palladium, nickel, tantalum and their alloys.

59. An acoustic transducer comprising:

a substrate;

a cover member having a planar surface and a support structure;

a diaphragm positioned between said cover member and said substrate, said diaphragm laterally movable within a plane parallel to said planar surface of said cover member, wherein the support structure engages the periphery of the diaphragm when the transducer is biased, to maintain the spacing of the diaphragm from the cover member.

60. The transducer of claim 59 wherein the cover member includes a plurality of perforations.

61. The transducer of claim 59 wherein the support structure is continuous.

62. The transducer of claim 59 wherein the support structure comprises a plurality of bumps.

63. An acoustic transducer comprising:

a substrate;

a cover member having a planar surface and a support structure;

a diaphragm;

means for suspending the diaphragm from the substrate to permit free movement of the diaphragm within its plane, wherein the support structure engages the periphery of the diaphragm when the transducer is biased, to maintain the spacing of the diaphragm from the cover member.

64. The transducer of claim 63, wherein the suspending means comprises high compliance springs.

65. The transducer of claim 63 wherein the support structure is continuous.

66. The transducer of claim 63 wherein the support structure comprises a plurality of bumps.

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FIG. 1

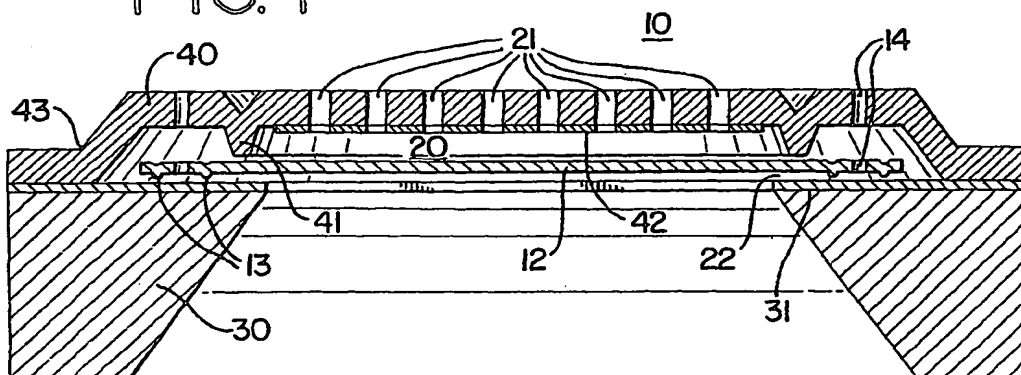
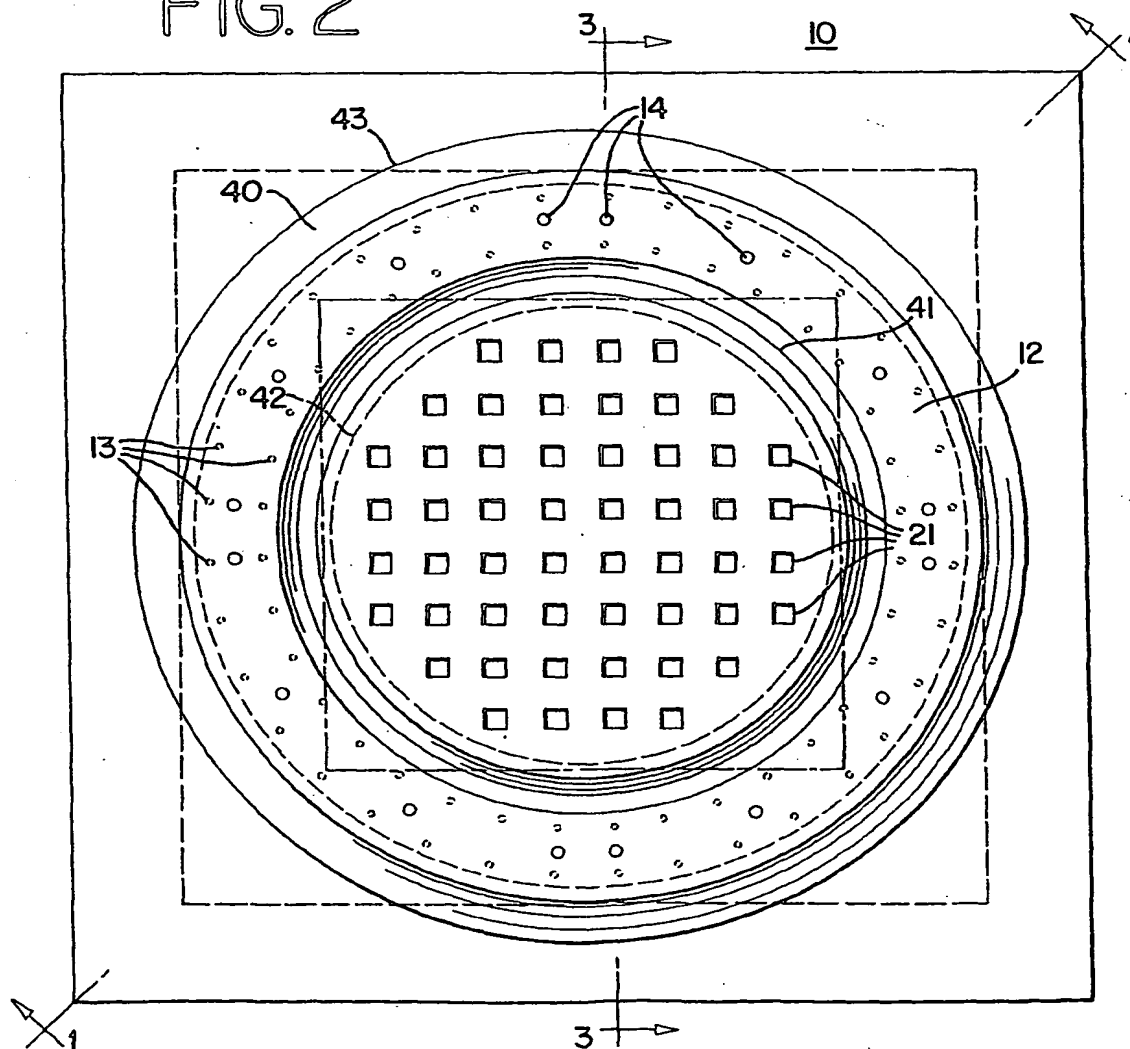


FIG. 2



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FIG. 3

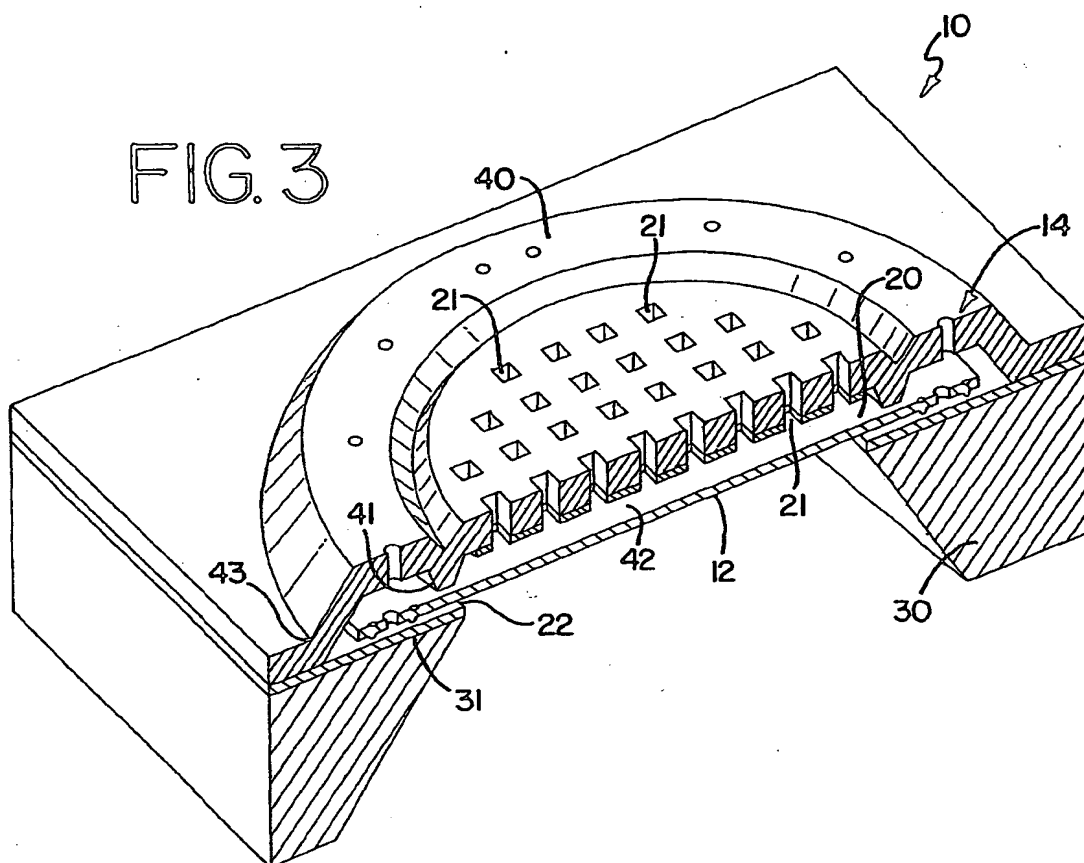
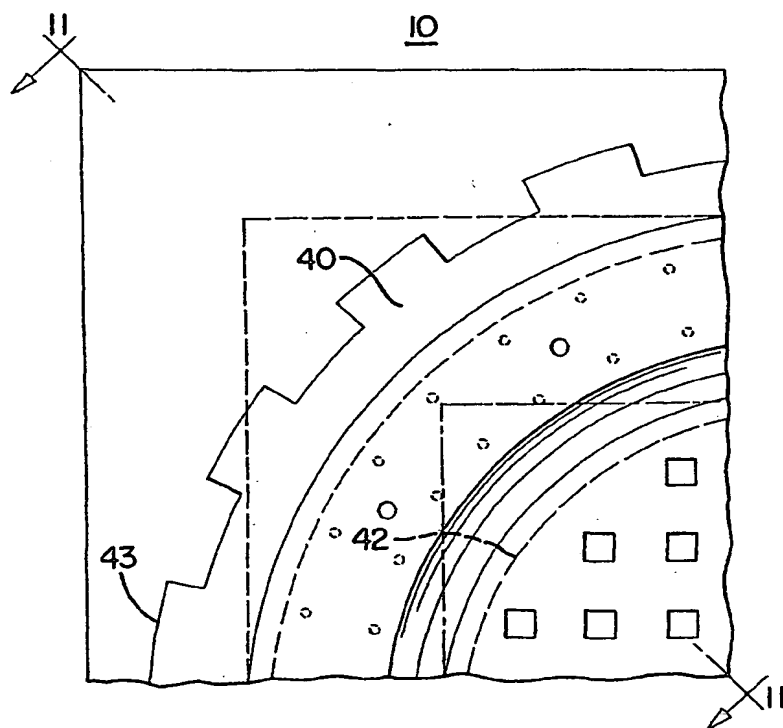


FIG. 4



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FIG. 5

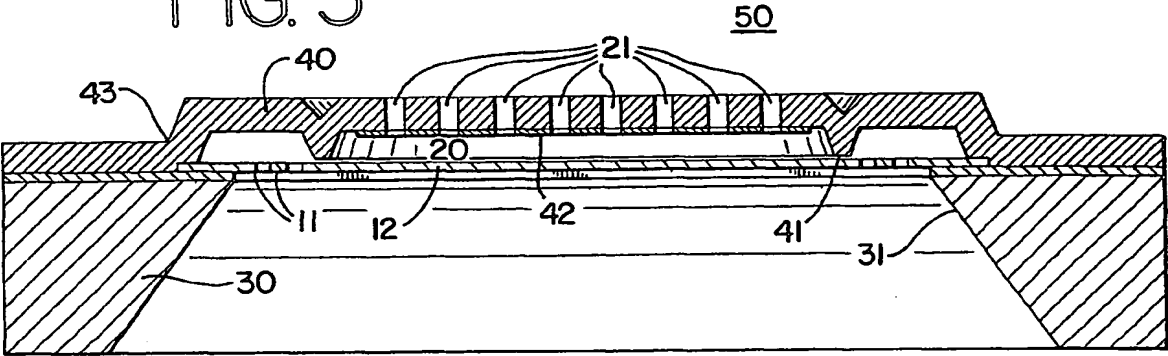


FIG. 6

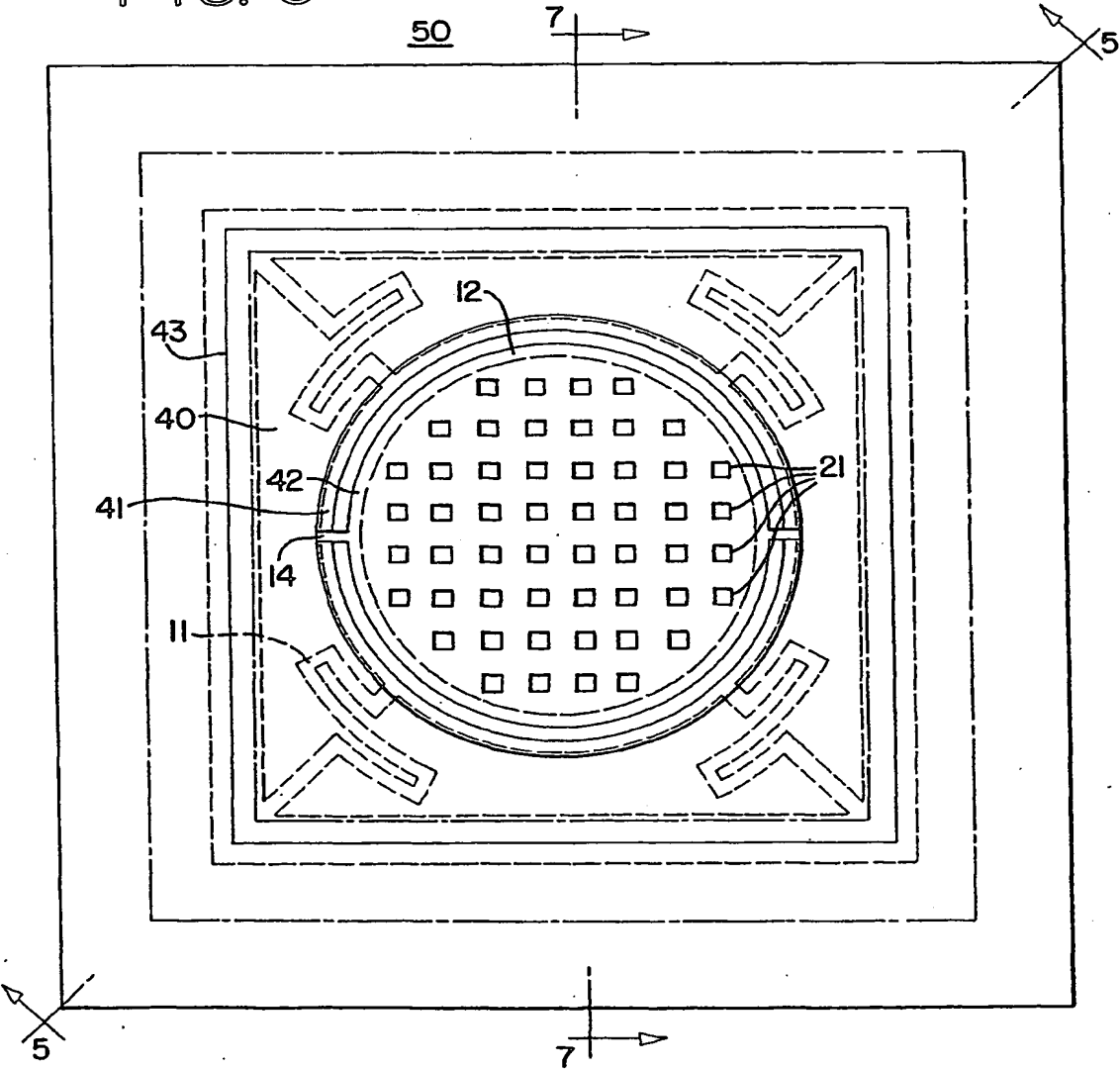


FIG. 7

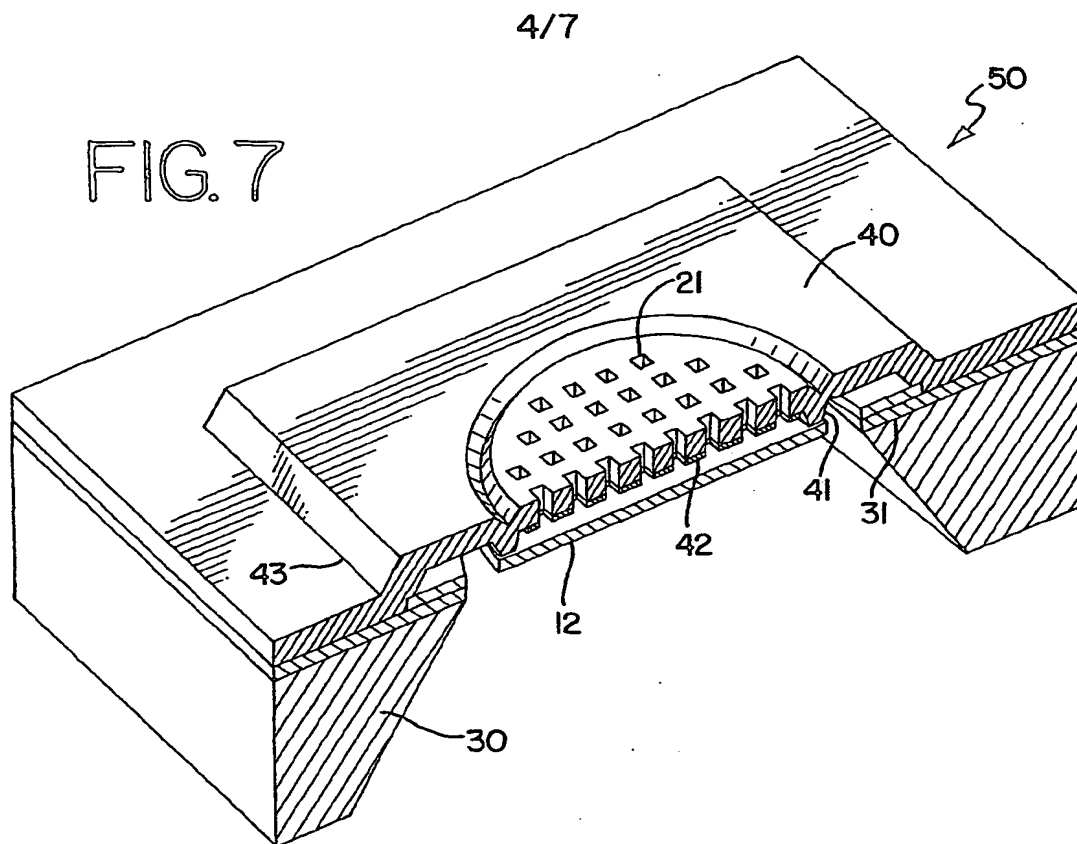
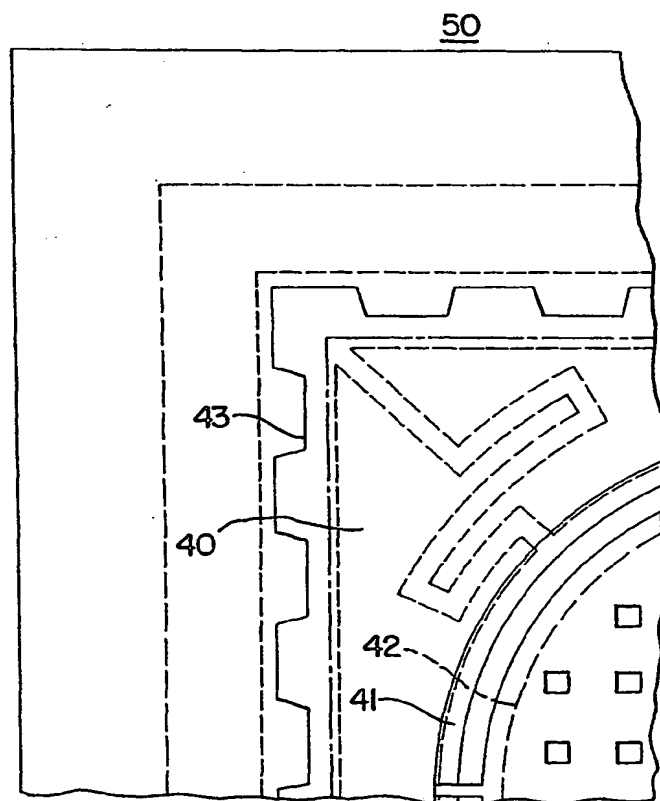


FIG. 8



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FIG. 9

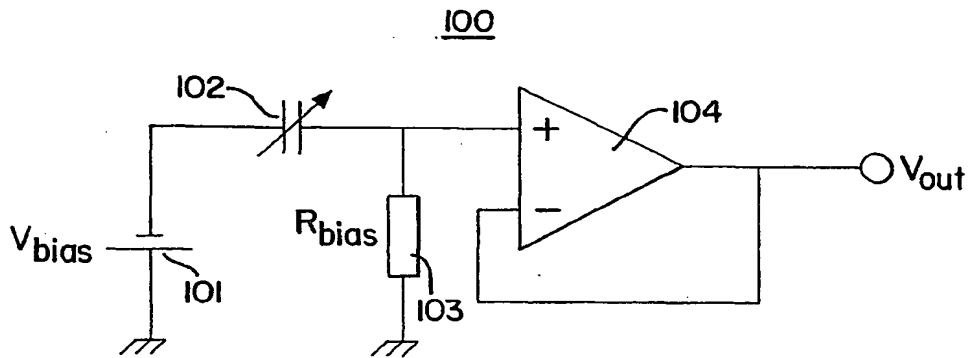
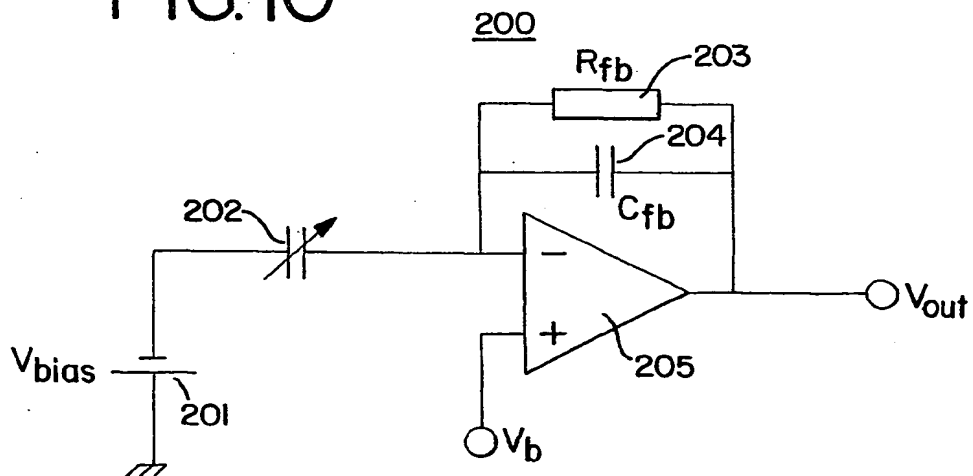


FIG. 10



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FIG. 11

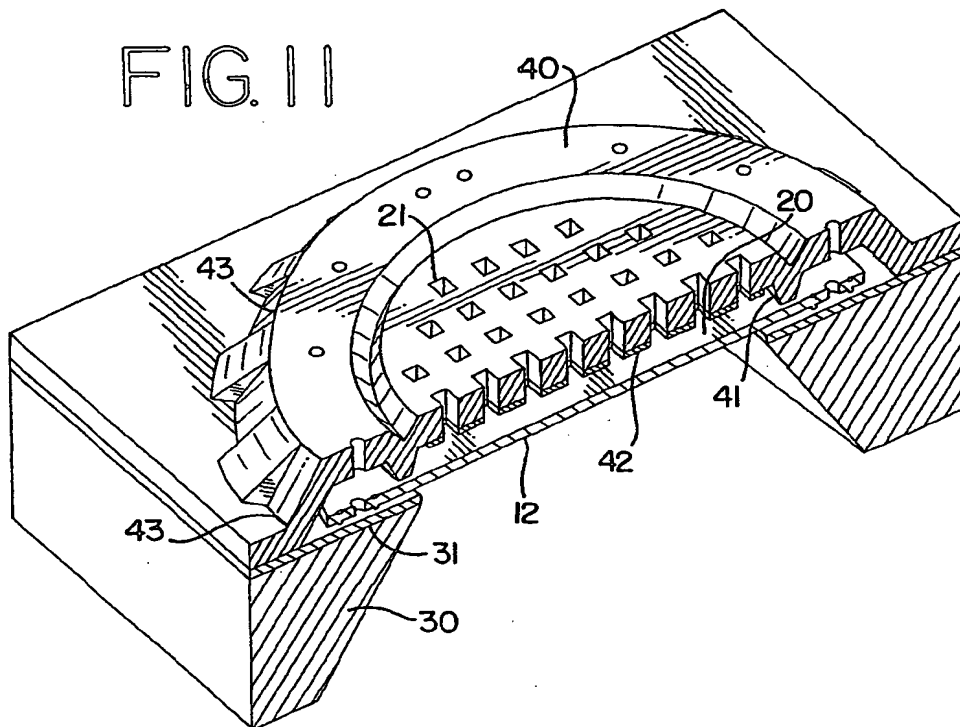
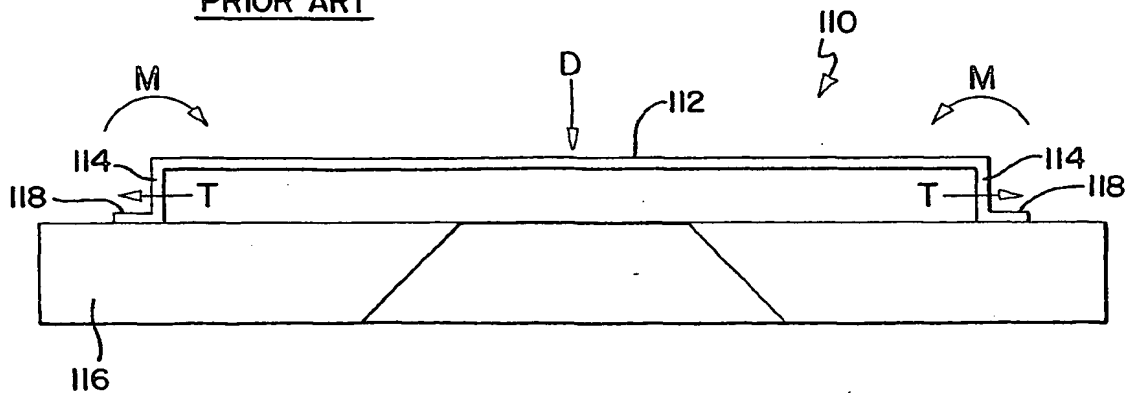


FIG. 12  
PRIOR ART



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FIG. 13

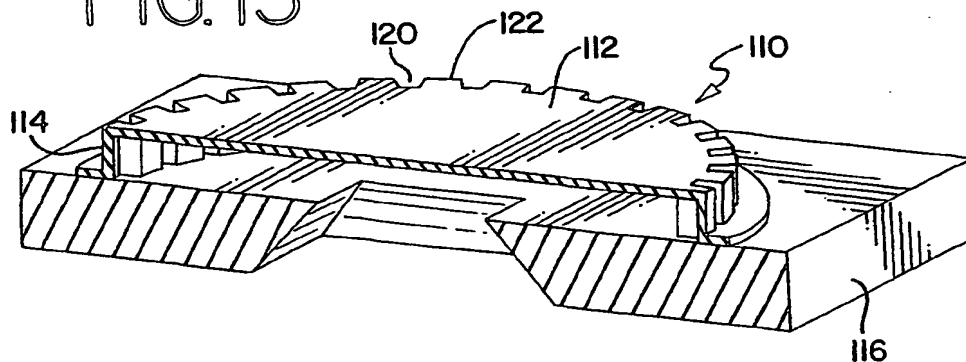


FIG. 14

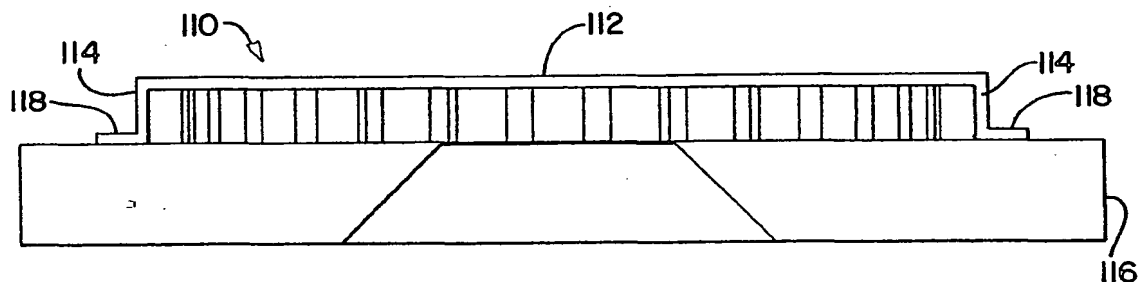


FIG. 15

